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Magnetostratigraphy of Oligocene - Miocene Glaciomarine Strata from CRP-2/2A, Victoria Land Basin, Antarctica

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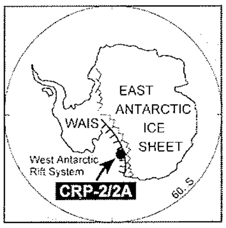

Abstract - We have used palaeomagnetic methods to constrain an age model for the 624.15 m succession of Oligocene-Miocene glaciomarine sediments recovered in the CRP-2/2A drillcore, McMurdo Sound, Antarctica. Identification of characteristic remanent magnetization (ChRM) directions on vector component plots demonstrates that secondary overprints have been successfully removed by stepwise alternating field demagnetization. Antipodal normal and reversed polarity inclination data and a conglomerate test within an intraformational breccia suggest that the ChRM directions are primary. Above 306.65 metres below sea floor (mbsf), a relatively low coercivity mineral dominates the magnetization. Below 306.65 mbsf, a high coercivity magnetic carrier is also observed in low intensity zones. The CRP-2/2A magnetic polarity zonation is subdivided into three intervals: (1) an upper 185.96-m-thick interval of alternating normal and reversed polarity (magnetozones N1-R5), (2) a thick interval of normal polarity between 185.96 and 441.22 mbsf (magnetozone N6), and (3) a lower 183.93-m-thick interval of alternating normal, reversed and indeterminate polarity as well as zones with shallow inclinations (magnetozones N7-?R12). Between 26 and 306.65 mbsf, the CRP-2/2A drillcore is uppermost Oligocene - lower Miocene in age with high average sediment accumulation rates (~1000 m/m.y.). Correlation with the magnetic polarity time scale (MPTS) is mostly straightforward and is constrained by biostratigraphic datums, and by $^{40}Ar/^{39}Ar$ and $^{87}Sr/^{86}Sr$ ages. An angular unconformity is identified at 306.65 mbsf and marks a major hiatus of up to 5 m.y. in duration. Below 306.65 mbsf, the CRP-2/2A drillcore is early Oligocene in age. The magnetic polarity record comprises numerous polarity zones, some of which may represent late Oligocene cryptochrons or geomagnetic excursions and definitive correlation with the MPTS is not possible with the existing data. While multiple hiatuses make it difficult to correlate the CRP-2/2A magnetic polarity record with the MPTS, the resulting age model demonstrates that more time is missing in the numerous sequence-bounding unconformities than is preserved in the CRP-2/2A drillcore.

INTRODUCTION

The goal of the Cape Roberts Project (CRP) is to obtain information about climate deterioration and the inception of glaciation in Antarctica during the Palaeogene as well as to learn more about the early rifting of this part of Gondwana and about uplift of the Transantarctic Mountains (Barrett & Harwood, 1992; Webb & Wilson, 1995). The original plan was to drill three stratigraphically overlapping holes through what was believed to be a continuous succession of more than 2000 m of Cenozoic sediments beneath the western Ross Sea, offshore from Cape Roberts, Antarctica. Marine geophysical surveys indicated that this succession includes the oldest sedimentary strata beneath the Ross Sea (Cooper & Davey, 1987). It was hoped that drilling near Cape Roberts would extend the record from the CIROS-1 drillcore, which was drilled in 1986, 70 km south of Cape Roberts. The oldest material obtained from the CIROS-1 drillcore is Late Eocene in age (Barrett et al., 1989; Wilson et al., 1998).

The first phase of CRP drilling took place in October, 1997. This phase was terminated prematurely when an unexpected storm weakened the sea ice drilling platform (Cape Roberts Science Team, 1998a). As a result, CRP-1 coring recovered only a 147.69 m drillcore comprising a *c.* 100 m succession of early Miocene strata beneath about 45 m of Quaternary cover (Cape Roberts Science Team, 1998b, 1998c; Roberts et al., 1998).

The second phase of CRP drilling took place in October and November, 1998. Initial drilling led to the recovery of a 57 m sedimentary succession in the CRP-2 drillcore. However, there were problems in setting the sea riser in unconsolidated sediment on the sea floor, and it was necessary to reset the drill-string (Cape Roberts Science Team, 1999). After drilling resumed at the same location, the hole was designated as CRP-2A.

Drilling of the composite CRP-2/2A drillcore reached 624.15 metres below sea floor (mbsf) and includes an unexpectedly thick Oligocene - early Miocene sedimentary succession (Cape Roberts Science Team, 1999). The hole terminated in earliest Oligocene strata (Wilson, Bohaty et al., this volume), which makes the basal sediments about 3 m.y. younger than the oldest strata (late Eocene, Chron

C16r) found in CIROS-1 (Wilson et al., 1998). The top of CRP-2/2A overlaps the lower part of CRP-1.

The sediments recovered in the CRP-2/2A drillcore are entirely glaciomarine and vary between massive bioturbated mudstones and coarse, poorly sorted diamictites and conglomerates (Cape Roberts Science Team, 1999). Facies associations (Powell et al., this volume) and their organization as cyclic sequences with sequence-bounding unconformities (Fielding et al., this volume) demonstrates that there was variability in the extent of glaciation through the Oligocene and early Miocene. In this paper, we present palaeomagnetic data, which we use to develop a magnetic polarity stratigraphy for the CRP-2/2A drillcore. We then correlate this magnetic polarity stratigraphy to the magnetic polarity time scale (MPTS, Cande & Kent, 1992a, 1995; Berggren et al., 1995) using the constraints imposed by biostratigraphic datums (Hannah et al., this volume; Scherer et al., this volume; Watkins & Villa, this volume) and $^{40}Ar/^{39}Ar$ (McIntosh, this volume) and $^{87}Sr/^{86}Sr$ (Lavelle, this volume) ages. Development of an age model is aimed at determining average sediment accumulation rates and to quantify the time preserved in sedimentary cycles as well as the time missing at disconformities and sequence-bounding unconformities.

In the initial reports of the Cape Roberts Science Team (1999), we gave a preliminary assessment of all data available at the end of the drilling season. However, at that point, time constraints did not permit measurement of all the palaeomagnetic samples. In addition, some palaeomagnetic samples required the sensitivity of a cryogenic magnetometer and others were mechanically unsuitable for measurement with the high-speed spinner magnetometer used at the Crary Science and Engineering Center (CSEC) at McMurdo Station (Cape Roberts Science Team, 1998a).

In this report, we incorporate new data from samples that were measured after the drilling season. Therefore, the results presented here supersede those reported by the Cape Roberts Science Team (1999), which were inherently preliminary in nature. The new data have allowed us to refine the magnetic polarity zonation, particularly for the lower 250 m of the CRP-2/2A drillcore where the data density has more than doubled. In addition, we report on new studies of rock magnetic properties and of field tests of palaeomagnetic stability.

METHODS

SAMPLING

One thousand and eleven palaeomagnetic samples were collected from the CRP-2/2A drillcore. Where possible, samples were taken at 0.5 m intervals in order to minimize the chance of missing short polarity intervals. However, where the lithology is coarse-grained or unconsolidated, the sampling density was often lower. The CRP-2/2A succession was deposited in a glaciomarine environment, therefore diamictites and other coarse-grained sediments are common. The silt-sized matrix of a diamictite is potentially useful for palaeomagnetic study, so samples were selected from fine-grained horizons whenever possible. However, there was often no alternative but to directly sample the diamictites or other coarse-grained lithofacies. Care was taken in the interpretation of data from these samples because the orientation of coarse sand grains, granules and pebbles would not have been controlled by magnetic forces and hence would not provide information about the geomagnetic field at the time of deposition.

Most of the upper 100 m of the CRP-2/2A drillcore and two sandy intervals that extended from 185.96 to 193.69 mbsf (lithostratigraphic unit 9.1) and from 280.75 to 286.80 mbsf (part of lithostratigraphic unit 9.8) are poorly consolidated and were sampled with 6.25 cm^3 plastic cubes (12% of the samples). The remainder of the drillcore is generally well lithified and it was possible to drill conventional cylindrical palaeomagnetic samples using a diamond-core drill that was mounted on a modified drill press (88% of samples). Cores and cubes were oriented with respect to vertical and also with respect to a drillcore recovery scribe line (Cape Roberts Science Team, 1999). Because of breaks in coring and recovery, the scribe line was not always continuous across drillcore breaks and fractures. Paulsen et al. (this volume) have reconstructed several stratigraphic intervals of the drillcore by matching drillcore segments across fractures and breaks. They have then used dipmeter and borehole televiewer (BHTV) imaging to azimuthally reorient these reconstructed intervals. We have used these limited reoriented intervals to determine true palaeomagnetic declinations, to determine the effect of stratal tilt on palaeomagnetic inclinations, and to conduct field tests of palaeomagnetic stability. However, we have not relied on azimuthal orientation of the drillcore for determining a magnetic polarity stratigraphy for the CRP-2/2A drillcore. The earth's magnetic field had steep inclinations (±83.4° assuming a geocentric axial dipole model) at the latitude of the CRP-2/2A site throughout the Cenozoic. As a consequence, the palaeomagnetic inclinations are sufficient to determine the polarity of samples from the CRP-2/2A drillcore. Because samples are not generally azimuthally oriented, palaeomagnetic declinations (Fig. 1) are reported in the laboratory coordinate system where declinations are arbitrary.

PILOT STUDY

Forty-four pairs of samples, each separated stratigraphically by a few cm, were collected at 5-10 m intervals from varying lithofacies throughout the drillcore. These paired samples were used to determine whether alternating field (AF) or thermal demagnetization was the most suitable technique for routine treatment of palaeomagnetic samples. For the pilot study, one sample from each pair was subjected to stepwise AF demagnetization at steps of 5, 10, 15, 20, 25, 30, 40, 50 and 60 mT. The other sample was subjected to thermal demagnetization at 120, 180, 240, 300, 350, 400, 450, 500, 550, and 600 °C; for some samples an additional step was added at 625 °C. After each thermal demagnetization step, the magnetic susceptibility was measured to monitor for thermal alteration. Further heating was abandoned if the susceptibility increased by more than about 30%, with concomitant loss of coherence

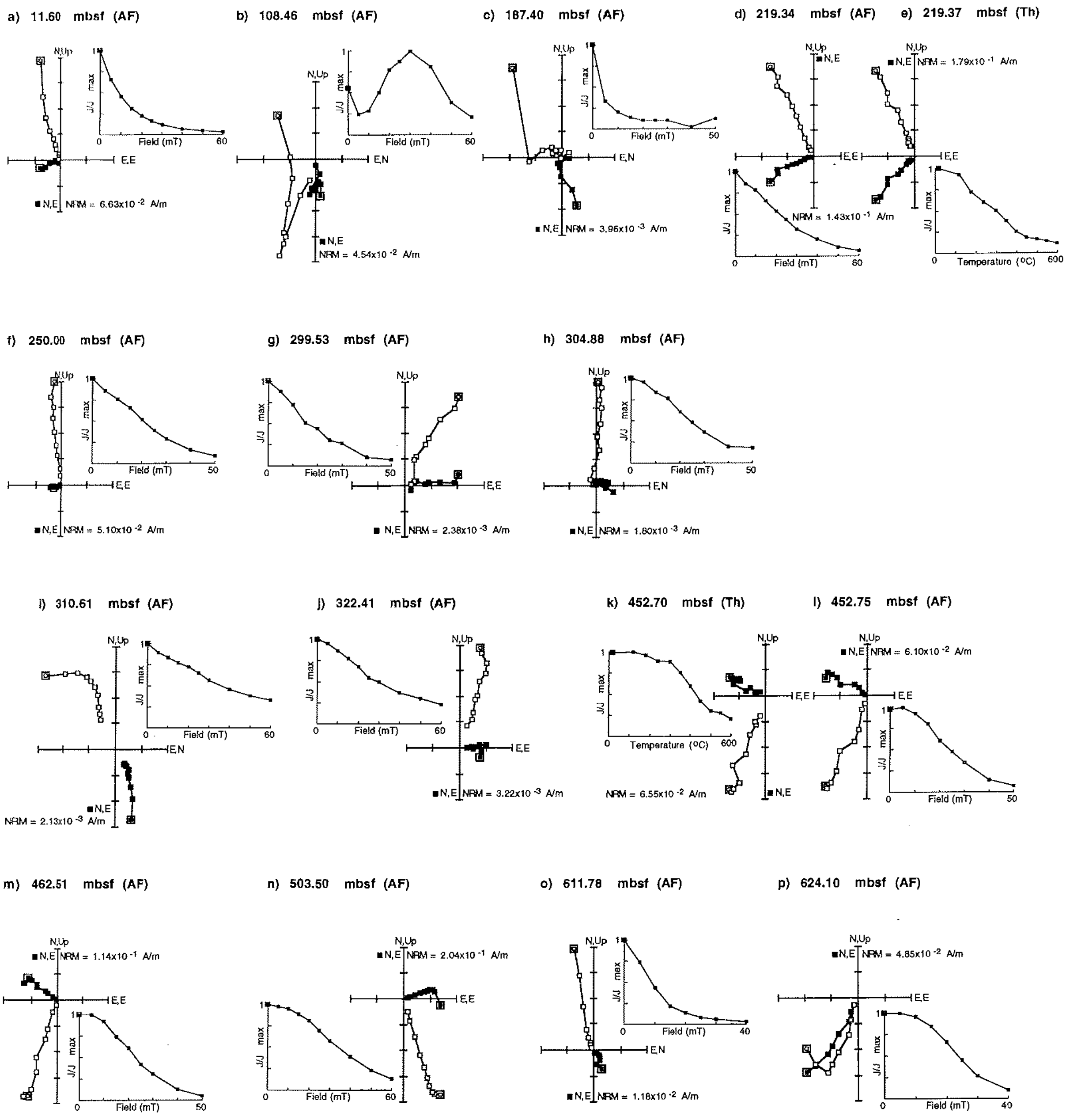

Fig. 1 - Vector component diagrams of demagnetization behaviour of representative samples from the CRP-2/2A drillcore. Samples are not azimuthally oriented and declinations are reported in the laboratory coordinate system with respect to the split face of the drillcore. Declinations are, therefore, arbitrary. Samples were oriented with respect to vertical. AF demagnetization of samples from: (a) 11.60 mbsf, (b) 108.46 mbsf, and (c) 187.40 mbsf. Comparison of AF and thermal demagnetization from: (d) 219.34 and (e) 219.37 mbsf, respectively. AF demagnetization of samples from: (f) 250.00 mbsf, (g) 299.53 mbsf, (h) 304.88 mbsf, (i) 310.61 mbsf, and (j) 322.41 mbsf. Comparison of thermal and AF demagnetization from: (k) 452.70 and (l) 452.75 mbsf, respectively. AF demagnetization of samples from: (m) 462.51 mbsf, (n) 503.50 mbsf, (o) 611.78 mbsf, and (p) 624.10 mbsf. Open (closed) symbols represent projections onto the vertical (horizontal) plane.

of the magnetic signal. All of the pilot studies were carried out at McMurdo Station, where an AGICO JR-5A spinner magnetometer was used for the magnetic measurements (Cape Roberts Science Team, 1998a).

MEASUREMENTS

Of the 1011 samples collected, 54% were cylindrical cores that were stepwise demagnetized and measured at McMurdo Station. Reasonably complete polarity results were obtained down to 370 mbsf and less complete results were obtained for the remaining 254 m of the drillcore (Cape Roberts Science Team, 1999). Another 5% of the samples were cylindrical cores that did not withstand the high-speed spinning required by the JR-5A magnetometer. The remainder of the cylindrical cores (29% of the samples) were judged to be too friable or too fractured for measurement on the JR-5A magnetometer at McMurdo Station (10.5%) or could not be measured at McMurdo Station due to time constraints (18.5%). Most of the samples in the latter category were from the lower 254 m of the drillcore. The cylindrical cores that remained after the drilling season, including the fragile ones, were measured on the automated, pass-through cryogenic magnetometer in the Palaeomagnetism Laboratory of the University of California, Davis. The remaining 12% of samples were collected from

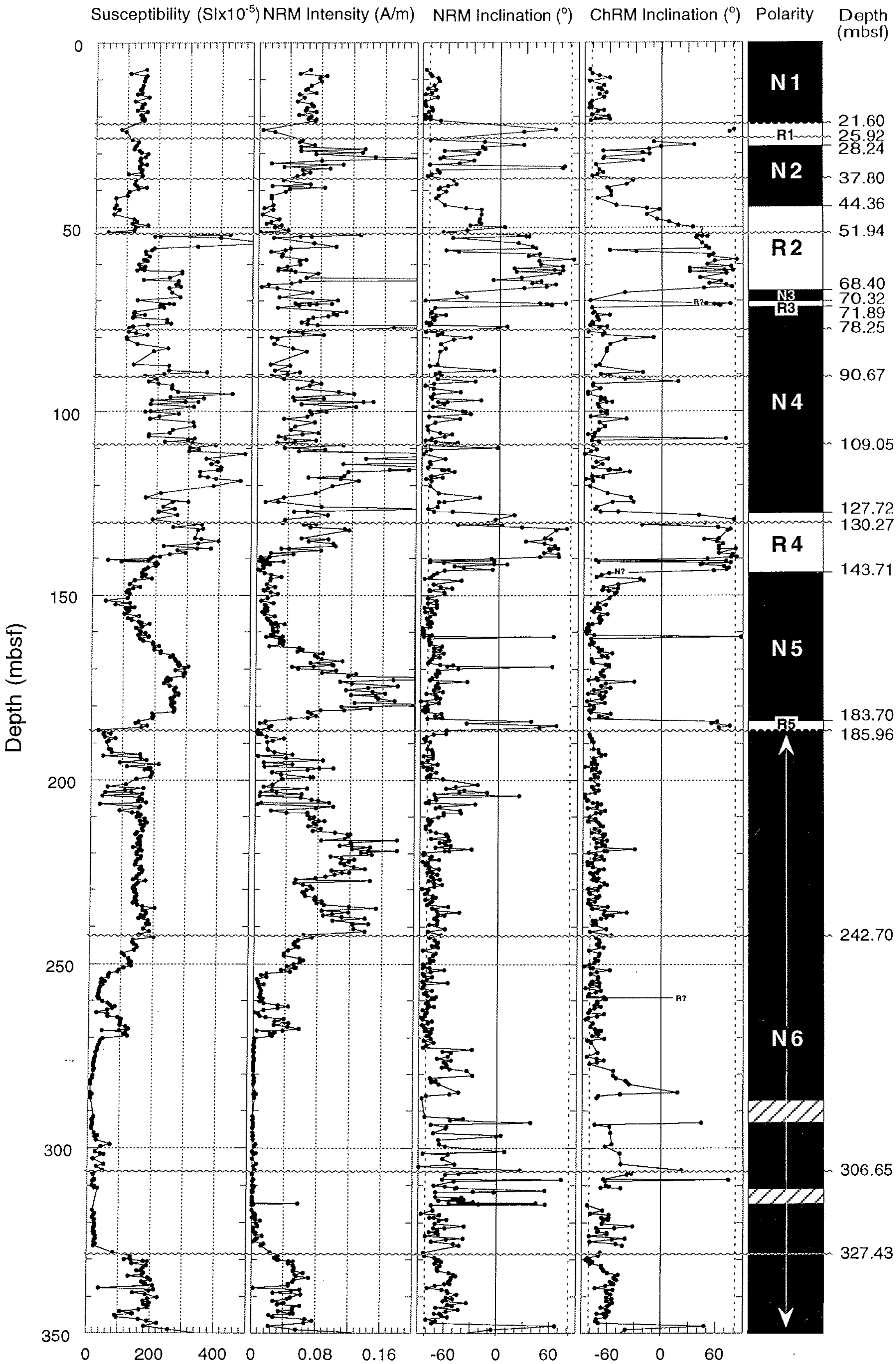

Fig. 2 - Down-core variations of magnetic susceptibility, natural remanent magnetization (NRM) intensity, NRM inclination, inclination of the characteristic remanent magnetization (ChRM) component and the magnetic polarity zonation (black = normal polarity, white = reversed polarity) for the CRP-2/2A drillcore. R? (N?) denotes samples that display a clear trend toward reversed (normal) polarity but for which a stable ChRM was not reached before the remanence intensity became too weak to measure. Hatching represents intervals where it was not possible to determine polarity due to poor drillcore recovery, unsuitable lithologies, intraformational deformation, or where it was not possible to determine ChRM directions.

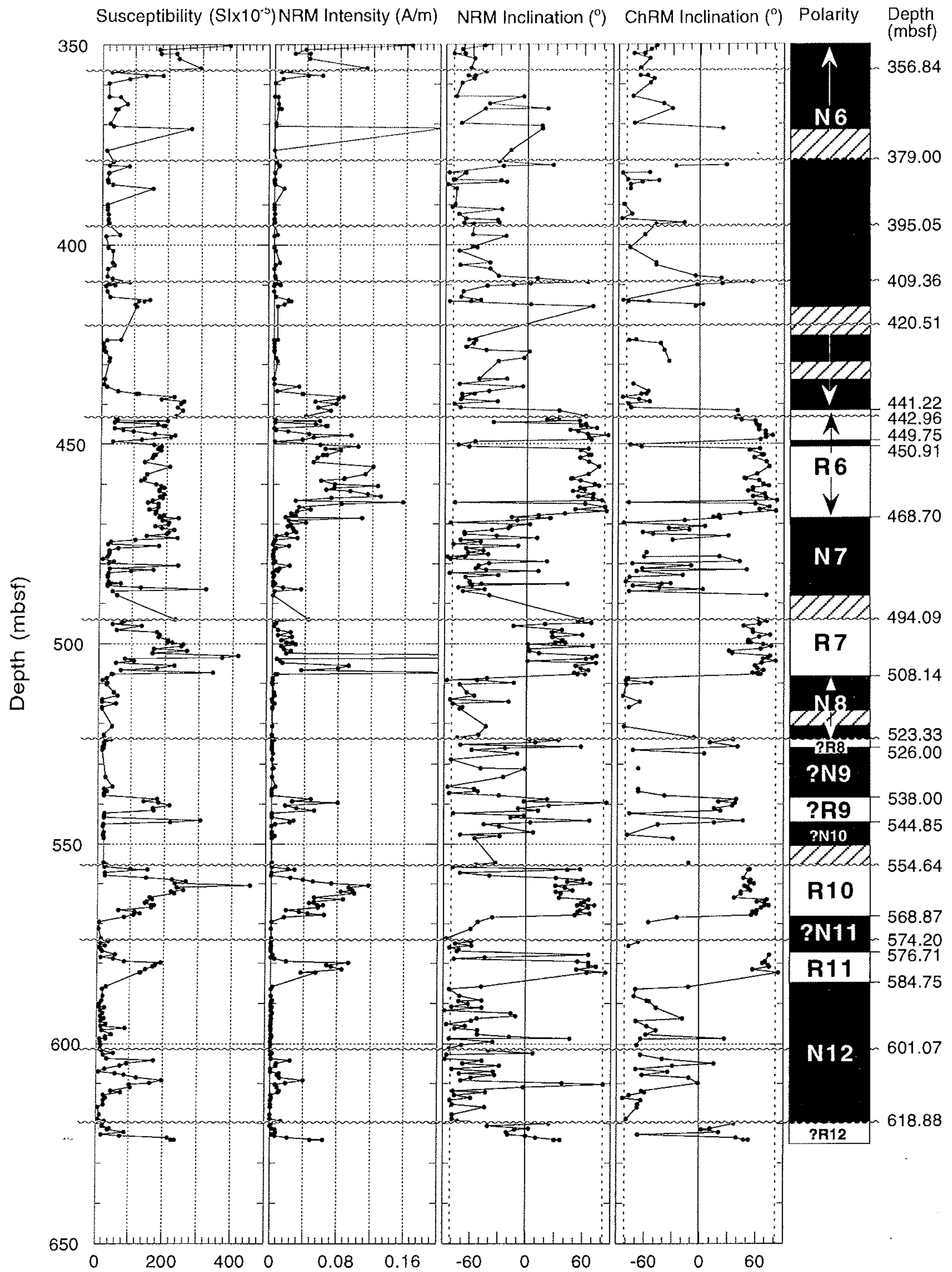

Fig. 2 - Continued.

unconsolidated intervals of the drillcore using plastic cubes. They had been transported to California during the drilling season and were also measured on the automated, pass-through cryogenic magnetometer. Those results were included in the initial report for the CRP-2/2A drillcore (Cape Roberts Science Team, 1999).

Low-field magnetic susceptibility (κ) was routinely measured at the CSEC using a Bartington Instruments magnetic susceptibility meter with an MS-2 sensor. Additional rock magnetic studies were conducted on samples that had been AF-demagnetized and also on chips or powders collected during sampling. These results are presented here if they are relevant for understanding the palaeomagnetic behaviour. A more detailed presentation of the magnetic properties is given in Verosub et al. (this volume).

RESULTS

PALAEOMAGNETIC BEHAVIOUR

The pilot study demonstrated that thermal and AF demagnetization are equally effective in removing secondary remanence components and in isolating the

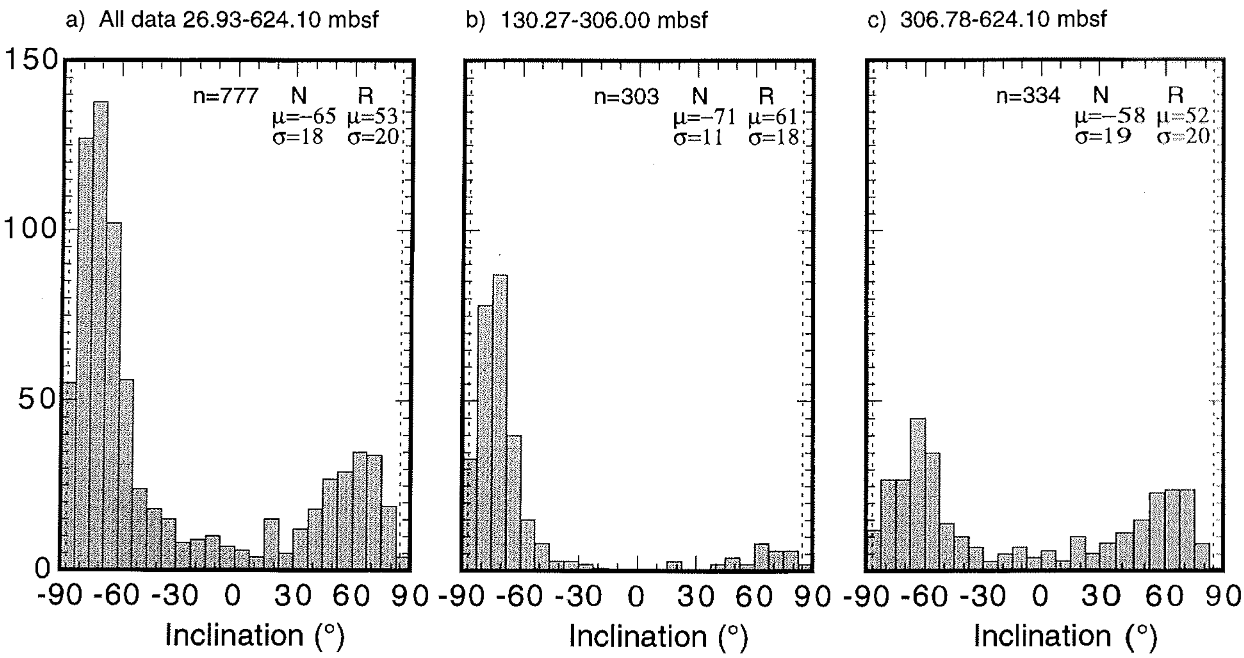

Fig. 3 - Histograms of palaeomagnetic inclinations without correction for stratal tilt for the CRP-2/2A drillcore (from Fig. 2). (a) All data below 26.93 mbsf, (b) all data between 130.27 and 306.65 mbsf (uppermost Oligocene – lowermost Miocene), and (c) all data below 306.78 mbsf (lower Oligocene). n = number of specimens analysed, μ = mean normal and reversed inclination values (assuming a Gaussian arithmetic distribution), σ = standard deviation of inclination values (also assuming a Gaussian arithmetic distribution). In all cases, the inclinations are shallower than expected (±83.4∞; shown by dashed lines) for a geocentric axial dipole field at the CRP-2/2A drillsite latitude (77°S). The inclinations appear to be shallower below 306.65 mbsf than above this level, which indicates that the disconformity at 306.65 mbsf probably represents an angular unconformity (see discussion in text).

characteristic remanent magnetization for both normal and reversed polarity samples (Fig. 1 d & e, k & l). The relative effectiveness of the two techniques did not vary between intervals of relatively high and low NRM intensity. AF demagnetization was therefore adopted for routine treatment of samples for the entire drillcore because it is less time-consuming than thermal demagnetization and because it avoids thermal alteration.

Upon demagnetization, many of the samples display a low coercivity, near-vertical, normal polarity component that may be a viscous or drilling-induced overprint. In most cases, this component was removed with peak alternating fields of less than 20 mT (*e.g.,* Fig. 1a, j & p). In some cases, the overprint and the original remanence had completely overlapping coercivity spectra, and it was not possible to isolate the two components (*e.g.,* Fig. 1h & o). Such samples were excluded from the magnetostratigraphic interpretation. In some cases, particularly in sandy lithologies (*e.g.,* 199.64 - 212.10 mbsf), another overprint is present. This overprint consistently has a nearly horizontal inclination and a declination that is directed away from the cut face of the drillcore (*e.g.,* Fig. 1i). Magnetic field measurements at the CRP drill-site core preparation facility indicated that the overprint probably resulted from a relatively strong magnetic field produced by rotation of the saw blade that was used to split the drillcores. When present, it replaces the viscous or drilling-induced overprint. In most cases, it can be removed by peak alternating fields of 10 - 20 mT.

As noted above, the glaciomarine sediments of CRP-2/2A often contain coarse sands and larger clasts, and, when these are present in samples, they can give rise to spurious palaeomagnetic results. Such samples usually display abnormal palaeomagnetic directions and are readily detected (*e.g.,* Fig. 1c). Samples exhibiting this behaviour were not included in the magnetostratigraphic interpretation.

Stable palaeomagnetic behaviour was found in 820 of the 963 samples that did not disintegrate during measurement (*e.g.,* Fig. 1a, b, d-h, j-n & p). The magnetic polarity zonation for the CRP-2/2A drillcore is shown in figure 2. In most cases, the characteristic remanent magnetization (ChRM) was determined using a principal component analysis (Kirchvink, 1980) that was constrained to include multiple demagnetization steps and the origin of a vector component diagram (*e.g.,* Fig. 1). In a few cases, the analysis was not constrained to include the origin. For a small number of samples, the polarity of the ChRM component was clear, but because of a low signal/noise ratio or incomplete removal of secondary components, the final direction of magnetization could not be precisely determined. In these cases, the results are represented on figure 2 as either "N?" or "R?".

INCLINATION SHALLOWING

ChRM inclinations for the CRP-2/2A drillcore have a bimodal distribution that demonstrates the existence of two stable polarity states (Fig. 3a). These distributions have steep normal and reversed polarity inclinations. However, mean normal (–65°, σ = 18) and reversed (+53°, σ = 19) polarity inclinations are much shallower than would be expected (±83.4°) for the 77°S latitude at the CRP-2/2A site (assuming a geocentric axial dipole field; Fig. 3). Paulsen et al. (this volume) demonstrated that this inclination shallowing is due to the tilt of strata recovered in CRP-2/2A. They matched the strata across breaks between drillcore sections and used imagery from the BHTV to azimuthally reorient 130 m of the CRP-2/2A drillcore between 200 and 447 mbsf. The reoriented sections between 130.27 and 306.00 mbsf were rotated back to horizontal (using the bedding correction of Jarrard et al., this volume). The resulting mean reoriented and bedding-corrected palaeomagnetic inclination is –81.6°, with α_{95} = 3.6° (Fig. 4), which is indistinguishable from the expected inclination for an axial geocentric dipole field at the CRP-2/2A site latitude. The mean inclination for the azimuthally reoriented normal polarity interval between 326.68 and 348.53 mbsf is –68.9°, with α_{95} = 4.0° (Paulsen et al., this volume). The difference in mean inclination between the above two intervals suggests a significant angular unconformity at the 306.65 mbsf sequence-bounding unconformity. Beneath 306.65 mbsf, mean inclinations (55°) are ~14° shallower than those above 306.65 mbsf. The apparent shallowing of inclinations in the lower part of CRP-2/2A may also be due in part to an inclination error; this phenomenon is commonly reported in sediments where bioturbation is limited or absent (Verosub, 1977) and where sediment has undergone significant compaction after deposition (Anson & Kodama, 1987; Arason & Levi, 1990).

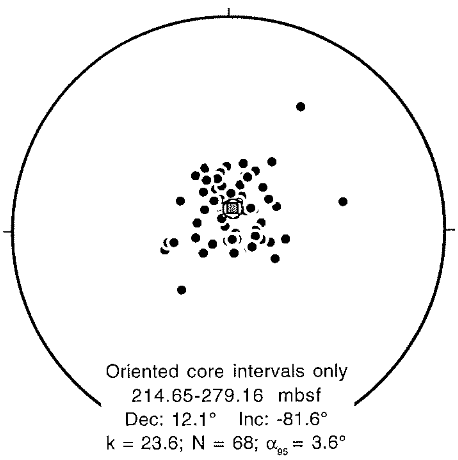

Fig. 4 - Equal area stereoplot showing individual ChRM palaeomagnetic vectors for azimuthally reoriented and bedding-corrected (Paulsen et al., this volume) drillcore intervals between 214.65 and 279.16 mbsf. Filled symbols represent ChRM vectors plotted in the upper hemisphere (normal polarity). The resulting mean inclination (-81.6°; shaded square) is close to that expected for a geocentric axial dipole field (83.4°) at the CRP-2/2A site latitude (77°S) and indicates that shallowing of palaeomagnetic vectors is most likely due to stratal tilt.

FIELD TESTS OF PALAEOMAGNETIC STABILITY

Laboratory demagnetization experiments have allowed identification of ChRM directions, as described above. However, laboratory tests alone cannot prove that a ChRM is primary. Field tests of palaeomagnetic stability (*e.g.*, Butler, 1992) can provide useful information, which can be used to assess the antiquity of a ChRM. Some field tests are difficult to conduct on drillcores (*e.g.*, the fold test) and much of the CRP-2/2A drillcore remains azimuthally unoriented, so a rigorous reversals test cannot be applied. However, it is possible to use a modified reversals test and a conglomerate test on the CRP-2/2A drillcore, as discussed below.

Reversals Test

Palaeomagnetic polarity is almost exclusively normal within the azimuthally reoriented intervals between 130.27 and 306.00 mbsf (Fig. 3b), which prevents comparison of normal and reversed polarity inclinations. Much of the reversed polarity in the CRP-2/2A drillcore occurs beneath 441.22 mbsf. However, as described above, inclinations from above and below the sequence-bounding unconformity at 306.65 mbsf cannot be directly compared (Fig. 3a). Below 306.65 mbsf, normal and reversed polarity inclinations are statistically indistinguishable (-58°, σ = 19; +52°, σ = 20; Fig. 3c), although the 1s uncertainties are high. This result suggests that the normal and reversed polarity data from the lower part of the CRP-2/2A drillcore are antipodal and that they pass a modified inclination-only reversals test.

Conglomerate Test

A conglomerate test on a 4.6-m-thick intraformational breccia within lithostratigraphic unit 11.1 provides additional evidence for the primary nature of the ChRM directions (Figs. 5 & 6). Eighteen individual clasts were sampled within the breccia and were subjected to stepwise AF demagnetization. The drillcore recovery scribe line is continuous through the brecciated interval. This allowed direct comparison of palaeomagnetic directions within the brecciated unit using the Watson (1956) test for randomness. Assuming that a distribution of measured palaeomagnetic vectors is random (the null hypothesis), the length of the resultant vector of measured directions (R) can be compared with the length of a resultant vector of the same number (N) of random directions (R_o) within specified probability limits of 1% and 5%. For N = 10, there is a 1%(5%) probability of R_o exceeding 5.94(5.03) in a random distribution. For the intraformational breccia in CRP-2/2A, R = 5.01 and the hypothesis of randomness cannot be rejected at the 95% probability level (Fig. 6b). As a comparison, we also examined azimuthally reoriented drillcore intervals above and below the intraformational breccia. These intervals gave R values of 9.50 and 9.69, respectively (Fig. 6a & c), which enables rejection of the hypothesis of randomness at the 99% probability level (R_o = 5.94).

ROCK MAGNETISM

Rock magnetic properties vary throughout the drillcore (Verosub et al., this volume). Above 270 mbsf, the relatively high magnetic susceptibility (Fig. 2a), relatively low coercivities (*e.g.*, Fig. 8) and thermomagnetic behaviour (Fig. 9) suggest that the magnetic mineralogy is dominated by magnetite and/or titanomagnetite. The thermomagnetic data also indicate the presence of a small high temperature component due to hematite. Below 270 mbsf, zones with high susceptibility and high NRM intensity alternate with zones of low susceptibility and low NRM intensity (Fig. 2b). The rock magnetic properties of these high susceptibility zones are

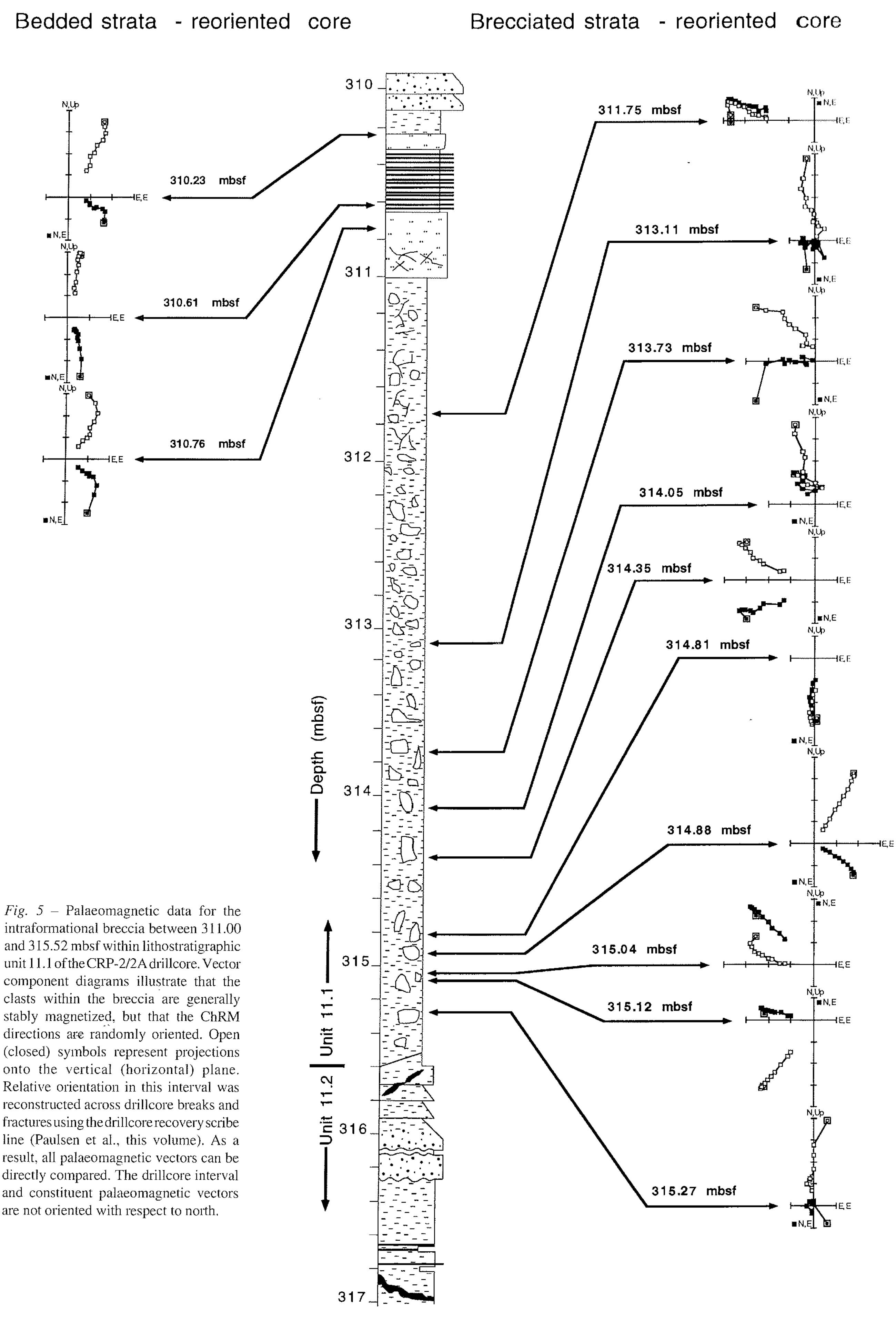

Fig. 5 – Palaeomagnetic data for the intraformational breccia between 311.00 and 315.52 mbsf within lithostratigraphic unit 11.1 of the CRP-2/2A drillcore. Vector component diagrams illustrate that the clasts within the breccia are generally stably magnetized, but that the ChRM directions are randomly oriented. Open (closed) symbols represent projections onto the vertical (horizontal) plane. Relative orientation in this interval was reconstructed across drillcore breaks and fractures using the drillcore recovery scribe line (Paulsen et al., this volume). As a result, all palaeomagnetic vectors can be directly compared. The drillcore interval and constituent palaeomagnetic vectors are not oriented with respect to north.

similar to those for the interval above 270 mbsf. The low susceptibility zones have a higher coercivity component than the high susceptibility zones (Verosub et al., this volume), although the similarity of AF and thermal demagnetization behaviour throughout these intervals demonstrates that the low coercivity phase is dominant enough that AF demagnetization can be used for all samples. This conclusion is consistent with the observed range of median destructive fields between 15 and 30 mT (Fig. 1).

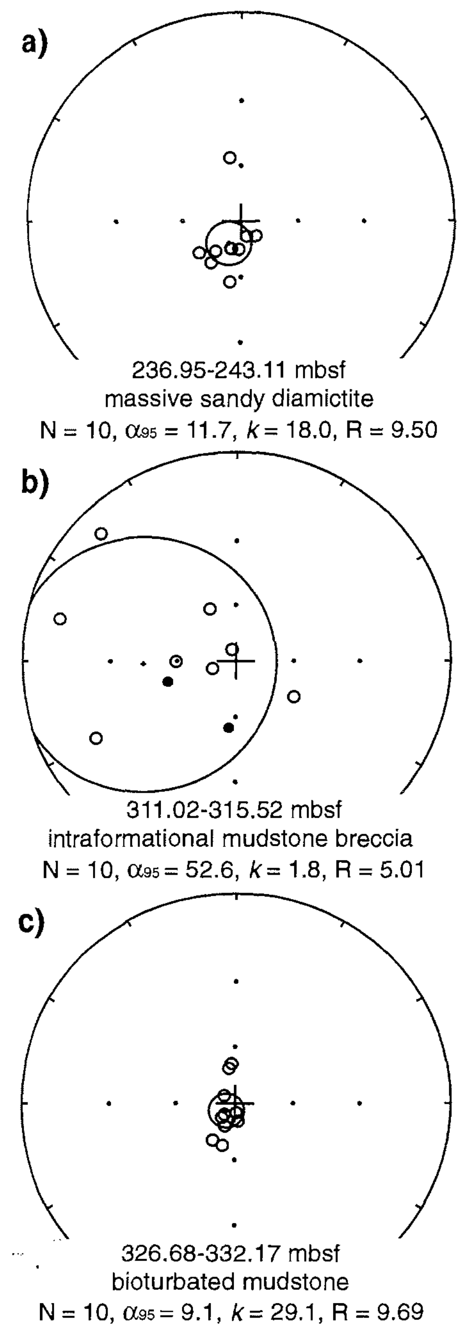

Fig. 6 – Equal area stereoplots showing individual palaeomagnetic vectors, calculated mean palaeomagnetic directions, and Fisher statistical parameters for reoriented drillcore intervals: (a) above the intraformational breccia (236.95 – 243.11 mbsf), (b) within the intraformational breccia (311.02 – 315.52 mbsf), and (c) below the intraformational breccia (326.68 – 332.17 mbsf). For N = 10, there is a 1%(5%) probability of R_0 exceeding 5.94(5.03) (Watson, 1956). Randomness cannot be disproved in the synformational breccia ($R < R_0$) but it can be disproved in the reconstructed intervals of drillcore above and below the breccia ($R >> R_0$). The drillcore intervals shown in the figure are neither absolutely oriented with respect to north nor are they corrected for stratal tilt.

MAGNETIC POLARITY STRATIGRAPHY

We have updated the preliminary magnetic polarity stratigraphy for the CRP-2/2A drillcore (Cape Roberts Science Team, 1999) by including data from an additional 205 samples that displayed stable palaeomagnetic behaviour. These additional samples are primarily from the lower 250 m of the drillcore where the data density has more than doubled (Fig. 2). The polarity record can be divided into 24 magnetozones: 12 of dominantly normal polarity and 12 of dominantly reversed polarity. Magnetozones are defined as intervals with several continuous samples with inclinations that are distinctly different from neighbouring intervals. In most cases, each magnetozone is defined by samples with inclinations that are antipodal from the neighbouring magnetozones and are of definite normal or reversed polarity. However, in magnetozones ?R8, ?R9 and ?R12, while inclinations are distinctly different from the neighbouring magnetozones, they are shallower than expected for reversed polarity samples at the latitude of the CRP-2/2A drillsite (assuming a geocentric axial dipole field). These magnetozones are marked on figure 2 with a question mark and are treated with caution when interpreting the magnetic polarity stratigraphy. The base of magnetozone R1 is also difficult to position because of shallow inclinations. Magnetozones ?N9, ?N10, and ?N11 are defined by relatively few samples that are more widely spaced than samples from other magnetozones. These are also marked on figure 2 with a question mark and are treated with caution when interpreting the magnetic polarity stratigraphy.

In many of the magnetozones, there are occasional samples that have opposite polarities to those of the rest of the magnetozone (Fig. 2). In each case, the palaeomagnetic behaviour is stable, and the presence of a steep normal polarity viscous or drilling-induced overprint suggests that the samples have not been inadvertently inverted (*e.g.*, Fig. 1b). These samples are believed to represent short-period geomagnetic fluctuations, such as geomagnetic excursions, that are recorded in the CRP-2/2A drillcore because of the high sediment accumulation rates and high sampling density. Such isolated samples are not used to define polarity zones.

Boundaries between magnetozones are placed either at the midpoint between successive samples of opposite polarity or at a lithological contact or disconformity that separates such samples. Where a magnetozone boundary is not defined by a lithological contact or disconformity, the precision in locating the boundary is determined by the sampling interval and the sediment accumulation rate. Given the high sampling density and the high average sediment accumulation rates in the CRP 2/2A drillcore (see below), the average sample spacing is estimated to be about 2-5 k.y.

The upper 435 m of the CRP-2/2A drillcore is dominated by normal polarity (Figs. 2a, 3b, & 3c). The most likely explanation for this is the high sampling density, in a succession with high sediment accumulation rates, and that more than one normal polarity zone is juxtaposed at one or more of the many stratigraphic disconformities (Cape Roberts Science Team, 1999).

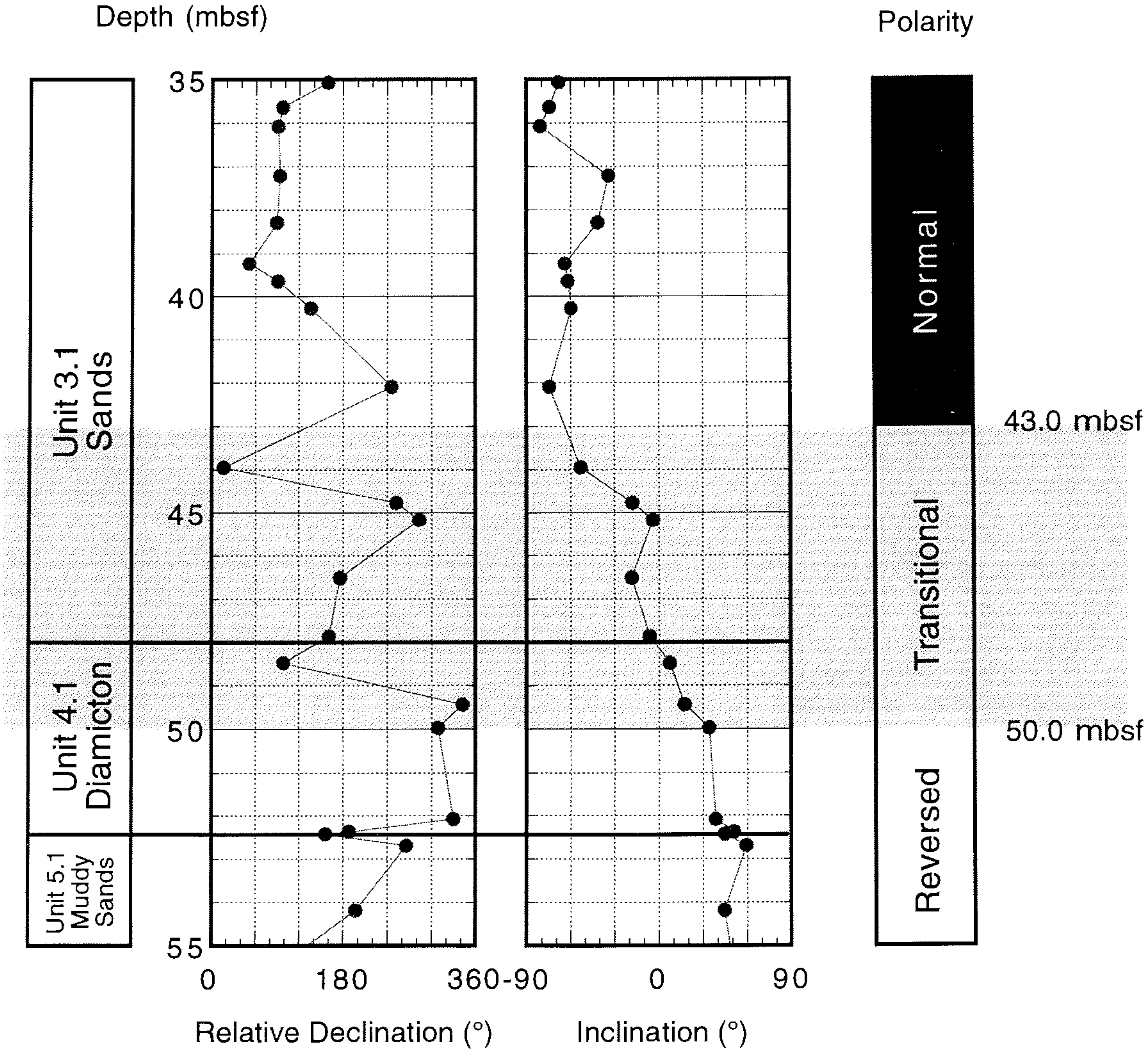

Fig. 7 - Variations in palaeomagnetic declination (arbitrary) and inclination (identified from principal component analysis of multiple demagnetization steps) through the inferred geomagnetic polarity transition (shaded) between magnetozones R2 and N2. The drillcore is not oriented with respect to north. The transition crosses the contact between lithostratigraphic units 4.1 and 3.1 and provides an estimate of accumulation rates and of rates of glacial processes (see discussion in text).

A significant number of discrete samples displayed inclinations that are intermediate between normal and reversed polarity (Figs. 2 & 3). In the majority of cases, these samples appear to be consistent with the presence of geomagnetic polarity transitions. The best example of this can be found between 43 and 50 mbsf (Fig. 7), where a transition from reversed to normal polarity is recorded across the boundary between lithostratigraphic units 4.1 (diamicton) and 3.1 (sands). Stable palaeomagnetic directions are observed within both lithostratigraphic units. It is known that it takes about 5 - 10 k.y. for a polarity transition to occur (Jacobs, 1994) and since transitional directions extend over an interval of about 7 m, sediment accumulation rates in this interval are probably on the order of 1-2 m/k.y. Such high accumulation rates are typical of glaciomarine environments (Powell et al., 1998).

A thick interval of normal polarity between 185.96 and 441.22 mbsf (Fig. 2) is designated as a single normal polarity magnetozone (N6). This magnetozone separates the magnetic polarity record of CRP-2/2A into 3 sub-equal intervals: a 186-m-thick upper interval of alternating normal and reversed polarity (magnetozones N1-R5); a middle 255-m-thick interval comprising a single normal polarity magnetozone (N6); and a lower 183-m-thick interval of alternating normal and reversed polarity (magnetozones R6-?R12).

The upper 185.96 m comprises 5 normal and 5 reversed polarity magnetozones. Lithostratigraphic unit 2.1 (Fig. 10), which is an unconsolidated, weakly-stratified diamicton that is the first lithostratigraphic unit recovered from CRP-2, is of entirely normal polarity and is designated as magnetozone N1 (Cape Roberts Science Team, 1999). It is separated from the underlying reversed polarity magnetozone (R1) by an unconformity surface at 21.60 mbsf. The sampling density in magnetozone R1 is low because lithostratigraphic unit 2.2 comprises mostly unconsolidated sands and diamicton and was difficult to sample. The lower boundary of magnetozone R1 is defined at the midpoint of a probable polarity transition at 28.24 mbsf. This boundary lies below a sequence-bounding unconformity at 25.92 mbsf, which marks the break between the Pliocene-Quaternary cover sediments and the

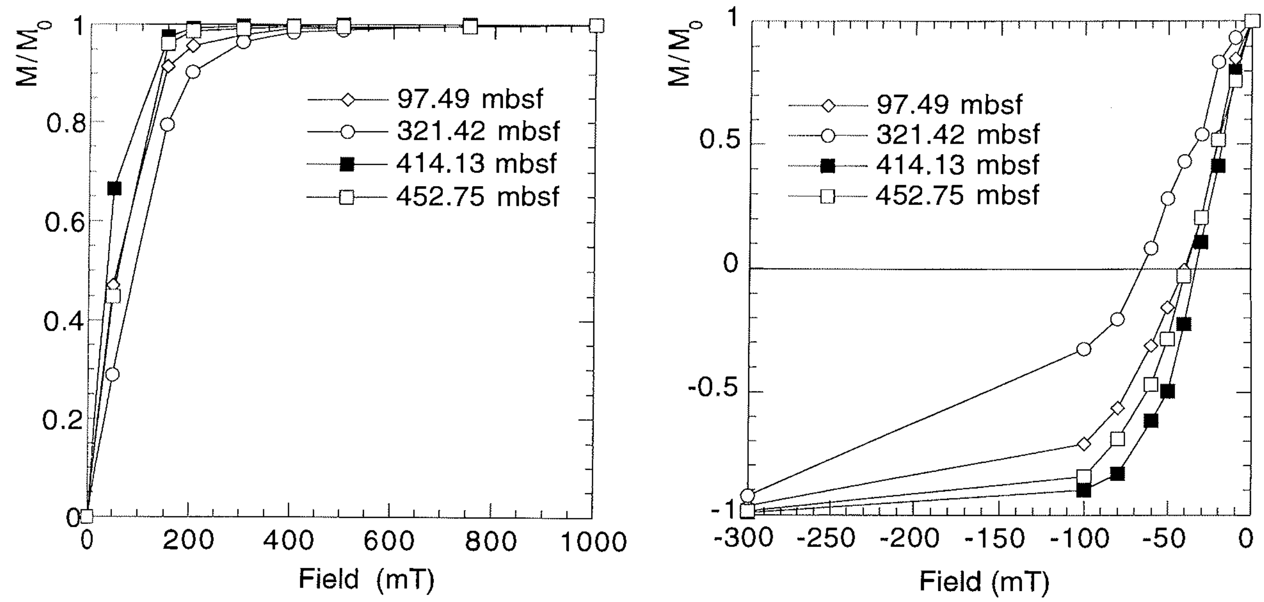

Fig. 8 - Plot of isothermal remanent magnetization (IRM) acquisition and DC demagnetization of representative samples from CRP-2/2A. Some samples have low coercivity (B_{cr} of about 40 mT) and saturate rapidly (below 300 mT) which indicates the dominance of low coercivity magnetic minerals. Other samples have high coercivity (B_{cr} of about 65 mT) and saturate above 300 mT, which indicates the presence of significant amounts of high coercivity magnetic minerals.

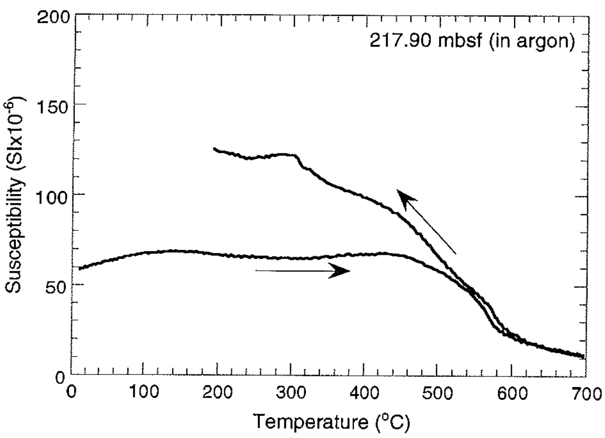

Fig. 9 - Low-field magnetic susceptibility vs. temperature for a sample from 217.90 mbsf in CRP-2/2A. The data indicate the presence of magnetite and possibly haematite (see discussion in text).

underlying Oligocene - Miocene stratigraphic succession (Cape Roberts Science Team, 1999).

The upper interval of the upper Oligocene – lower Miocene succession comprises several thick (20-50 m) and a few thin (~2 m) magnetozones. Normal polarity dominates the interval between 28.24 and 44.36 mbsf (magnetozone N2). The boundary between magnetozones R2 and N2 is marked by a ~7-m-thick record of transitional field directions, as discussed above (Fig. 7). This transition includes the lithological boundary between lithostratigraphic units 4.1 (diamicton) and 3.1 (sands), located at 48.00 mbsf.

Two thin magnetozones, N3 and R3, are recorded within the basal mudstone of lithostratigraphic unit 5.1. Magnetozone N4 (55.83 m thick) encompasses several lithostratigraphic units and stratigraphic disconformities, including three sequence-bounding unconformities. This suggests that magnetozone N4 might represent more than one polarity subchron of the MPTS. The boundary between magnetozones N4 and R3 occurs at a stratigraphic contact (71.89 mbsf) that is not interpreted as a sequence-bounding unconformity. The R4/N4 boundary does not occur at a lithostratigraphic break or disconformity but rather within a single diamictite (lithostratigraphic unit 8.1). Magnetozone R4 encompasses a major sequence-bounding unconformity at 130.27 mbsf (Cape Roberts Science Team, 1999). Immediately beneath the unconformity at 130.27 mbsf, palaeomagnetic inclinations have intermediate polarity (Fig. 2) which may represent a truncated polarity transition. It is likely, therefore, that two reversed polarity subchrons are amalgamated into magnetozone R4. Normal polarity dominates the interval from 143.71 to 183.70 mbsf (magnetozone N5) and a thin interval of reversed polarity (magnetozone R5) is truncated by the sequence-bounding unconformity at 185.96 mbsf. The boundaries between magnetozones N5 and R4 and between R5 and N5 do not appear to occur at disconformities; the N5/R4 boundary appears to include some transitional directions.

Magnetozone N6 is a thick (255 m) zone of normal polarity that represents the middle part of the CRP-2/2A drillcore. It contains several thin (< 10 m) zones in which the polarity is uncertain. For example, four intervals comprise poorly-consolidated sands (286.7 to 291.5 mbsf, 371 to 379 mbsf, 415.4 to 423.8 mbsf, and 429.2 to 433.6 mbsf), and it was either not possible to sample them or the samples did not withstand the rigours of measurement. It was also not possible to determine a meaningful magnetic polarity stratigraphy in the intraformational breccia (between 311.0 and 315.52 mbsf) as discussed above (Fig. 5). Magnetozone N6 encompasses several sequence-bounding unconformities, including an

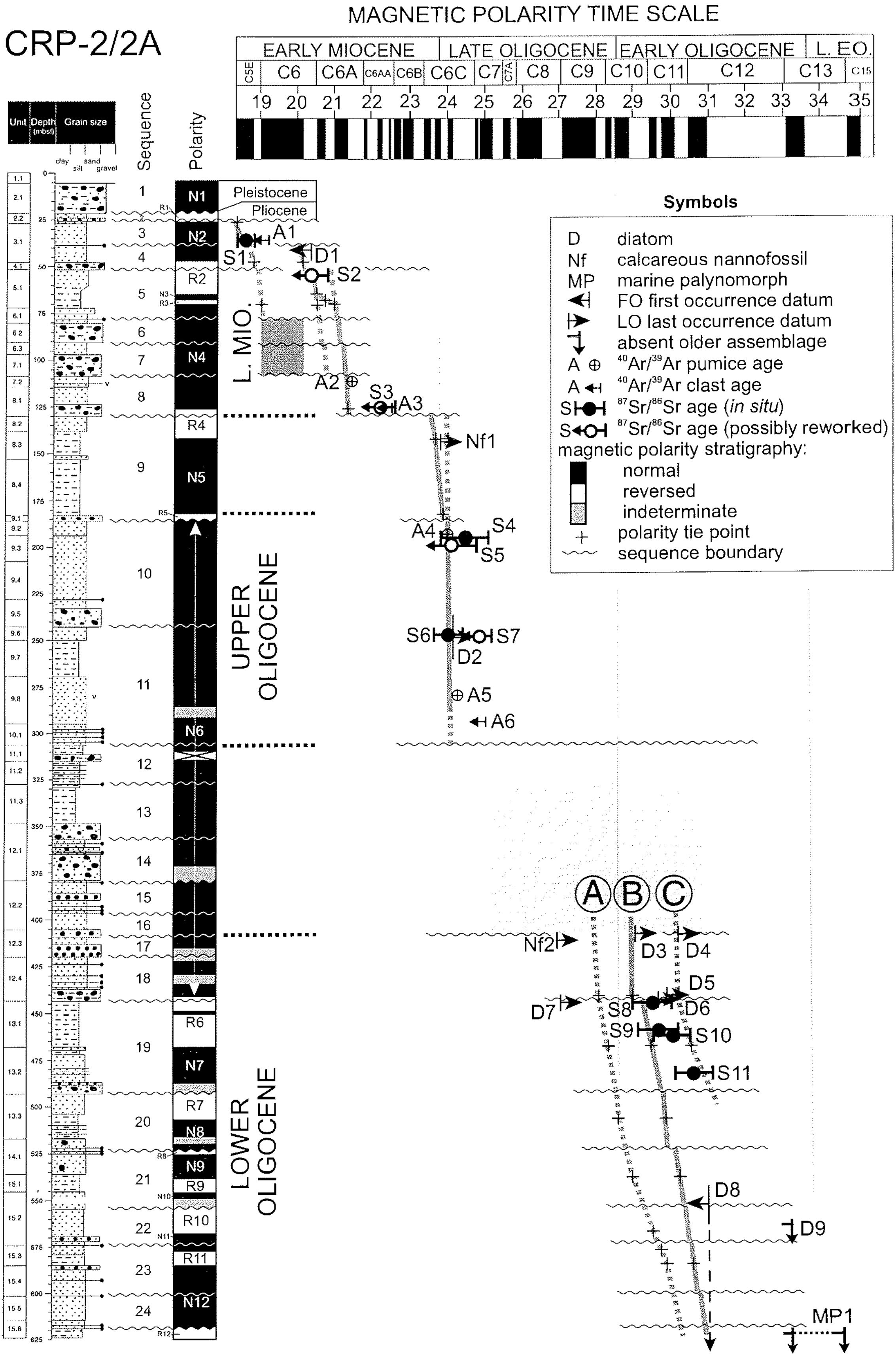

Fig. 10 - Correlation of the CRP-2/2A magnetic polarity zonation with the magnetic polarity time scale (MPTS) of Cande & Kent (1995) and Berggren et al. (1995). Black (white) denotes normal (reversed) polarity. Grey denotes intervals where it was not possible to determine the polarity due to unstable palaeomagnetic behaviour or to sampling gaps. The interval between 311 and 315.52 mbsf is an intraformational breccia and did not yield useful polarity data. Solid lines indicate preferred age-depth correlations; stippled lines indicate other possible correlations (see discussion in text). The shaded area represents the range of possible correlations between 306.65 and 409.36 mbsf where no correlation is possible with existing data. Wilson et al. (this volume) lists datum events, with alpha-numeric indicators. See text for discussion.

inferred major angular unconformity at 306.65 mbsf, and may therefore represent two or more amalgamated normal polarity subchrons. The polarity transition at the base of magnetozone N6 occurs within the basal diamictite of lithostratigraphic unit 12.4, 1.74 m above another major sequence-bounding unconformity at 442.96 mbsf (Cape Roberts Science Team, 1999).

The lower 183 m of the CRP-2/2A drillcore comprises 7 reversed and 6 normal polarity magnetozones (Fig. 2). Magnetozone R6 is dominated by reversed polarity, but it contains two thin normal polarity intervals at *c.* 450 and *c.* 464.5 mbsf. These intervals are represented by only one or two samples, respectively, and are not treated as full magnetozones. The upper part of magnetozone R6 contains a major sequence-bounding unconformity at 442.96 mbsf, which may have caused an amalgamation of more than one reversed polarity subchron. Samples from magnetozone N7 are predominantly of normal polarity, although the demagnetization behaviour is less stable than other intervals of the drillcore and the resultant palaeomagnetic directions are noisy. Samples from most of magnetozone N7 have weak remanence intensities, which contributes to the poor data quality in this interval. The boundary between magnetozones N7 and R6 contains several intermediate palaeomagnetic inclinations and spans the lithological contact between lithostratigraphic units 13.2 (sandstone) and 13.1 (mudstone; Fig. 10) at 468.70 mbsf. The transitional palaeomagnetic directions may indicate that there is no significant time gap at this lithological boundary. The boundary between magnetozones R7 and N7 is not well-determined because the interval between 487.96 and 494.09 mbsf is a coarse-grained, soft-sediment-deformed, clast-rich diamictite that was not sampled.

Magnetozone R7 occurs immediately below a sequence-bounding unconformity at 494.09 mbsf. The transition between magnetozones N8 and R7 occurs within a bioturbated and laminated siltstone (lithostratigraphic unit 13.3). The lower part of magnetozone N8 is poorly defined because the upper part of lithostratigraphic unit 14.1 (above the sequence-bounding unconformity at 523.33 mbsf) is a clast-rich coarse sandstone (Fig. 10) that is too coarse-grained for sampling. Abundant sandstone horizons between the sequence-bounding unconformities at 523.33 and 554.64 mbsf, respectively, restricted sampling. As a result, the boundaries between magnetozones are not precisely located within this interval of the drillcore, although a N-R-N-R polarity pattern (magnetozones ?N10-?R9-?N9-?R8) can be tentatively identified. Between the base of the drillcore (624.15 mbsf) and 554.64 mbsf, several sub-equal magnetozones define a R-N-R-N-R pattern (magnetozones ?R12-N12-R11-?N11-R10). This interval contains several sequence-bounding unconformities, but only one (at 618.88 mbsf) coincides with a magnetozone boundary. A lithological contact, which was not defined as a sequence-bounding unconformity, occurs at 568.87 mbsf and marks the boundary between magnetozones ?N11 and R10. The nature of the boundary between magnetozones R11 and ?N11 is not well determined because samples at this level did not yield stable magnetizations. There is also no obvious lithological contact in the vicinity of this magnetozone boundary. The boundary between magnetozones N12 and R11 is also ill-defined because of coarse sample spacing. However, it is likely that the lithological contact between lithostratigraphic units 15.4 (diamictite) and15.3 (laminated mudstones and fine sandstones) at 584.75 mbsf marks the boundary between magnetozones N12 and R11.

DISCUSSION

The polarity zonation shown in figure 2 is based on the interpretation of stepwise demagnetization data that pass strict stability criteria. Antipodal normal and reversed polarity inclination data, and a positive conglomerate test on an intraformational breccia, demonstrate that the remanence is primary and that we have effectively removed viscous overprints and secondary overprints that arose from drilling and cutting of the drillcore. Palaeomagnetic stability appears to be stratigraphically controlled: zones with high magnetic susceptibility and high remanence intensity are more stably magnetized and the data from such zones are of better quality than those from zones of lower susceptibility and lower remanence intensity. However, even in zones of low magnetic intensity it is still possible to identify clear ChRM components. Furthermore, mean palaeomagnetic inclination values from the lower *c.* 300 m of the CRP-2/2A drillcore are 30° different from the steep present-day field or coring-induced overprints, and they pass an inclination-only reversal test (Fig. 3d). These results indicate that the lower part of the CRP-2/2A drillcore contains coherently magnetized sediments that were magnetized prior to tilting and at or near the time of deposition. Therefore, it is reasonable to attempt to correlate the CRP-2/2A magnetic polarity zonation to the MPTS (Fig. 10).

In the nearshore glaciomarine successions recovered in the CRP-2/2A drillcore, there are significant variations in lithofacies and sediment accumulation rates, and there are multiple disconformities (Cape Roberts Science Team, 1999). therefore, the thicknesses of the magnetozones cannot be directly compared to the durations of polarity chrons and independent age constraints are required to develop a robust age model (Wilson et al., this volume). Sequence stratigraphic analysis indicates the presence of several major unconformities that subdivide the CRP-2/2A drillcore record. The most significant sequence-bounding unconformities occur at 130.27 and 306.65 mbsf (Cape Roberts Science Team, 1999; Fielding et al., this volume) and these unconformities divide the CRP-2/2A record into three major depositional successions. Constraints on the age of these depositional successions are discussed below.

$^{40}Ar/^{39}Ar$ AND $^{87}Sr/^{86}Sr$ AGES

Three volcanic ash horizons at 111-114 mbsf (A2; 21.44 ± 0.05 Ma), c. 193 mbsf (A4; 23.98 ± 0.13 Ma), and 280.03 mbsf (A5; 24.22 ± 0.06 Ma) were dated using the $^{40}Ar/^{39}Ar$ technique (McIntosh, this volume). A further three $^{40}Ar/^{39}Ar$ ages on volcanic clasts provide maximum ages at 36.02 mbsf (A1; 19.18 ± 0.26 Ma), 125.92 mbsf (A3; 22.56 ± 0.29 Ma) and 294.22 mbsf (A6; 24.98 ± 0.17 Ma), respectively (McIntosh, this volume).

Strontium isotope ratios from molluscan fragments provide age information at eleven stratigraphic horizons (Lavelle, this volume). Taphonomic studies suggest that shells from 36.25 mbsf (S1; 18.41-18.84 Ma), 194.89 mbsf (S4; 23.86-25.15 Ma), 246.99 mbsf (S6; 23.67-24.37 Ma), 445.05 mbsf (S8; 28.91-29.93 Ma), 460.66 mbsf (S9; 29.01-30.07 Ma), 463.37 mbsf (S10; 29.37-30.40 Ma), and 483.17 mbsf (S11; 29.83-31.12 Ma) are *in-situ*. Shells from 54.96 mbsf (S2; 19.74-20.93 Ma), 126.56 mbsf (S3; 21.85-22.63 Ma), 198.75 mbsf (S5; 23.74-24.45 Ma), and 247.69 mbsf (S7; 24.47-25.15 Ma) are abraded and probably reworked, but may provide maximum ages for each respective stratigraphic level (Lavelle, this volume).

BIOSTRATIGRAPHY

Biostratigraphy provides further constraints on the age interpretation of the CRP-2/2A drillcore through the recognition of nine diatom datums (Scherer et al., this volume) and two calcareous nannofossil datums (Watkins & Villa, this volume). The interval between 27 and 306.65 mbsf contains two diatom datums (D1: FO *Thallassiosira praefraga* complex, C6r, and D2: LO *Lisitzinia ornata*, C6Cr) and a nannofossil datum (Nf1: LO *Dictycoccites bisectus*, C6Cn.2r) that are in close agreement with $^{40}Ar/^{39}Ar$ and $^{87}Sr/^{86}Sr$ ages from this interval. Truncation of a diatom assemblage in a major sequence-bounding unconformity at 306.65 mbsf (Scherer et al., this volume) suggests that significant time may be missing at this horizon. Between 306.65 and 442.99 mbsf, fossil preservation is poor. However, two diatom datums (D3: LO *Eurossia irregularis*, C10, and D4: LO *Pyxilla reticulata*, C11r) at 405.39 mbsf and a nannofossil datum (Nf2: LO *Chiasmolithus altus*, C8n.2n) at 412.25 mbsf indicate a middle Oligocene age. At *c.* 440 mbsf, three diatom datums (D5: LO *Rhizosolenia antarctica*, C11n.2n, D6: LO *R. oligocaenica*, C11n.1r, and D7: LO *Asterolampra punctifera*, C9n) also suggest a middle Oligocene age. *Cavitatus jouseanus* (D8, C12n) occurs down to 564.63 mbsf and also in the upper part of the CRP-3 drillcore (Cape Roberts Science Team, 2000), which along with the absences of *Hemiaulus characteristicus* and the CIROS-1 "Assemblage B" (D9, C13n; Harwood, 1989) and the marine palynomorph "Transantarctic Assemblage" (MP1, C13n-C15n; Hannah, 1997), suggests that the CRP-2/2A drillhole terminated within the lower Oligocene.

CORRELATION TO THE MPTS

The magnetic polarity record of CRP-2/2A (Figs. 2 and 10) is characterized by thick normal polarity magnetozones above 441.22 mbsf. Each of these zones is punctuated by several sequence-bounding unconformities (Fielding et al., this volume) and many other lithological contacts (Cape Roberts Science Team, 1999). It is therefore possible that each of these thick normal polarity magnetozones represents the juxtaposition of two or more normal polarity subchrons.

Between 25.92 and 51.94 mbsf, the FO of *T. praefraga* (D1) and the $^{40}Ar/^{39}Ar$ age on a volcanic clast (A1) suggest that the R2-N2 transition correlates with the C6r-C6n transition or possibly with the C5Er-C5En transition (Fig. 10). Above the unconformity at 37.80 mbsf, A1 and S1 suggest that the upper part of magnetozone N2 correlates with C5En and that the N2-R1 transition correlates with the C5En-C5Dr transition. Between 51.94 and 130.27 mbsf, correlation to the MPTS is constrained by the volcanic ash horizon at 113 mbsf (A2). Subchron C6Ar (21.32 – 21.77 Ma; Cande and Kent, 1995; Berggren et al., 1995) spans the age represented by A2, however, in CRP-2/2A the volcanic ash lies toward the base of a thick normal polarity magnetozone (N4). It is unlikely that the ash is reworked, and, given the uncertainties in numerical ages assigned to $^{40}Ar/^{39}Ar$ standards and in the calibration of the MPTS in the early Miocene, it is likely that magnetozone N4 correlates with the nearest normal polarity subchron (C6An.2n). The immediately underlying reversed polarity zone (*i.e.*, the top of magnetozone R4, above the sequence-bounding unconformity at 130.27 mbsf) would then correlate with the top of C6Ar. Magnetozones R3-N3-R2 might then correlate with subchrons C6An.1r, C6An.1n, and C6r of the MPTS, respectively. This correlation suggests that lower Miocene average sediment accumulation rates were initially high and that magnetozone N4 correlates with only one subchron (C6An.2n) of the MPTS. It also suggests that average sediment accumulation rates then slowed considerably within the mudstone of lithostratigraphic unit 5.1. Such large variations in sedimentation rate are possible considering the significant variations in sedimentary facies in this interval of the CRP-2/2A drillcore. However, the presence of sequence-bounding unconformities at 78.25 mbsf, 90.67 mbsf and 109.05 mbsf, respectively (Fielding et al., this volume), makes interpretation of the palaeomagnetic stratigraphy between 37.80 and 109.05 mbsf ambiguous. It is also possible that the upper part of magnetozone N4, magnetozones R3 and N3 and the lower part of magnetozone R2 might correlate with subchrons C6An.2n to C6An.1r, or alternatively, with C6An.1n to C6r, or with C6n to C5Er (Fig. 10).

Between 185.96 and 306.65 mbsf, multiple age constraints (A4-A6, D2, and S4-S7) provide tight age control and the upper part of magnetozone N6 can be correlated with C6Cn.3n (latest Oligocene). The R5-N5-R4 polarity pattern between 185.96 and 130.27 mbsf is more problematical. The LO of *D. bisectus* (Nf1) and its associated assemblage mark the Oligocene – Miocene boundary in many other sections (Watkins & Villa, this volume). Our preferred correlation suggests that the N5-R4 transition is equivalent to the C6Cn.2n-C6Cn.1r transition and that Nf1 occurs within the lowest Miocene in the CRP-2/2A drillcore. Alternatively, the upper part of magnetozones N6 and N5 may both correlate with C6Cn.3n, which leaves magnetozone R5 with no equivalent in the MPTS. This alternative is difficult to explain because the polarity record is well defined in this interval (Fig. 2a) and the MPTS shows no indication of reversed polarity cryptochrons in the latest Oligocene or near the Oligocene-Miocene boundary (Cande & Kent, 1992a).

Age control between 306.65 and 409.36 mbsf is poor. By analogy to much of the overlying succession (130.27-306.65 mbsf), the presence of only normal polarity through this interval suggests that sedimentation was rapid (200-1000 m/m.y.) and that only one or two polarity subchrons are represented by this part of magnetozone N6. Multiple criteria suggest that significant time is missing in the unconformity at 306.65 mbsf (Wilson, Bohaty et al., this volume). However, the time interval encompassed by this hiatus or others at 327.43, 356.84, 379.00, 395.05, and 409.36 mbsf, respectively, cannot be determined with existing data.

The occurrence of *C. jouseanus* (D8) in CRP-3 (Cape Roberts Science Team, 2000) and the absence of the early Oligocene diatom "Assemblage B" (D9) and late Eocene marine palynomorph "Transantarctic Assemblage" (MP1) recovered in the CIROS-1 drillcore (Harwood, 1989; Hannah, 1997) constrain the age of the base of the CRP-2/2A drillcore. However, development of an age model that is consistent with all available age data for the lowermost 181 m of the CRP-2/2A drillcore is problematical. No unique interpretation of the magnetic polarity stratigraphy can accommodate all the $^{87}Sr/^{86}Sr$ and biostratigraphic data. Three possibilities are presented in figure 10 and are discussed below. The intervals of indeterminate polarity in this part of the drillcore and thin normal polarity intervals that are defined by only one or two samples are not considered in these correlations. The interpretation that best fits the $^{87}Sr/^{86}Sr$ data between 445 and 483 mbsf (correlation C in Fig. 10) suggests that sediments at the base of the hole were deposited during Chron C15 (Late Eocene). However, this interpretation is inconsistent with the diatom (D8 & D9) and marine palynomorph (MP1) data. A second interpretation (Correlation A, Fig. 10) is more consistent with the diatom (D8 & D9) and marine palynomorph (MP1) data, but it suggests that the strata between 445 and 483 mbsf were deposited in Chron C9 (early late Oligocene), which is younger than the $^{87}Sr/^{86}Sr$ data and diatom datums D5 and D6. This interpretation implies an uppermost Chron C12r (middle early Oligocene) age for the bottom of the hole which is consistent with preliminary results from the CRP-3 drillhole in which Oligocene strata have been recovered from an interval that lies stratigraphically below the CRP-2/2A drillcore (Cape Roberts Science Team, 2000). Both of these correlations to the MPTS (A & C; Fig. 10) suggest an average sediment accumulation rate of *c*. 60 m/m.y., with multiple short hiatuses occurring at sequence-bounding unconformities.

The discrepancy between $^{87}Sr/^{86}Sr$ and biostratigraphic and magnetostratigraphic data raises concern with respect to the robustness of the magnetic polarity record in the lower 180 m of the CRP-2/2A drillcore. Given the positive field tests of palaeomagnetic stability and clear differences between the ChRM and viscous or drilling-induced overprints in the CRP-2/2A sediments, it is unlikely that intervals of strata have been remagnetized, even in the weakly magnetized zones. Another consideration, however, is the occurrence of cryptochrons in the Oligocene MPTS (Cande & Kent, 1992a). In constructing the MPTS, Cande & Kent (1992a) noted short-period, low-amplitude anomalies ("tiny wiggles") in profiles of Eocene-Oligocene oceanic crust from fast-spreading ridges. The duration of these short anomalies is on the order of 30 k.y. or less and it is possible that they represent short-lived polarity intervals, or, alternatively, changes in the intensity of the dipole component of the earth's magnetic field (Blakely & Cox, 1972; Cande & LaBrecque, 1974; Cande & Kent, 1992b). With the assumed high average sediment accumulation rates in the CRP-2/2A drillcore (up to 1000 m/m.y.), cryptochrons may represent polarity intervals 20-30 m in thickness. It is, therefore, possible that not all magnetozones from the lower 180 m of the CRP-2/2A drillcore have equivalents in the MPTS and that several of the thinner magnetozones may represent cryptochrons. A further consideration, given the high sediment accumulation rates (~1000 m/m.y.) in the CRP-2/2A drillcore, is that some magnetozones with shallow inclinations (*e.g.*, magnetozones ?R8, ?R9, & ?R12) may represent geomagnetic excursions. An intermediate correlation may therefore be more appropriate on figure 10 (*e.g.*, correlation B). Several shear planes in the lower part of the CRP-2/2A drillcore (Passchier, this volume) also raise the possibility of repetition of strata in this succession. A more exact correlation with the MPTS is, therefore, not possible with the existing data. Even with these uncertainties, however, it appears that the lower 318 m of the CRP-2/2A record represents, at least in part, an interval that is missing at a major hiatus located at 366 mbsf in the CIROS-1 drillcore (Harwood et al., 1989; Wilson et al., 1998).

CONCLUSIONS

Identification of stable characteristic remanence components on vector component plots, antipodal normal and reversed polarity inclination data, a conglomerate test and rock magnetic measurements indicate that palaeomagnetic samples from the Oligocene - Miocene interval of the CRP-2/2A drillcore are generally stably magnetized and can be used to establish a magnetic polarity zonation for the drillcore. Twenty-four magnetozones are recognized (Figs. 10). A thick interval of normal polarity between 185.96 and 441.22 mbsf subdivides the CRP-2/2A polarity record into 3 intervals: a 186-m-thick upper interval of alternating normal and reversed polarity; a middle 225-m-thick interval comprising only normal polarity, and a lower 183-m-thick interval of alternating normal, reversed, and indeterminate polarity, as well as zones with distinctive but shallow inclinations.

Above 306.65 mbsf, correlation to the MPTS is mostly straightforward and is well-constrained by $^{40}Ar/^{39}Ar$ dates, $^{87}Sr/^{86}Sr$ ratios, and diatom and calcareous nannofossil datums (Fig. 10). Our preferred correlation between 27 and 130.27 mbsf suggests that sediment accumulation rates were on the order of 250 m/m.y. between 72.84 and 130.27 mbsf, and that they fell to about 25 m/m.y. in the more muddy and sandy strata between 27 and 72.84 mbsf. However, independent age data do not tightly constrain correlation of the palaeomagnetic stratigraphy between 37.80 and 109.05 mbsf and several alternative correlations are possible (Fig. 10). A two million year hiatus is identified at 130.27 m, which separates an overlying diamictite and sandstone succession from an underlying sandy mudstone and sandstone succession. Direct correlation with the MPTS between 130.27 and 185.96 mbsf is in conflict with nannofossil biostratigraphy (Watkins & Villa, this volume; Wilson et al., this volume), which makes it difficult to place the Oligocene-Miocene boundary in the CRP-2/2A drillcore. It may occur at *c.* 180 mbsf on the basis of palaeomagnetic evidence or within a hiatus at 130.27 mbsf on the basis of nannofossil evidence. Between 185.96 and 306.65 mbsf, an unambiguous correlation with the MPTS suggests that the rate of accumulation was extremely high (>1000 m/m.y.) and that the 120 m of sandstone, sandy mudstone and minor diamictite represents <119 k.y. of time in the latest Oligocene.

An angular unconformity at 306.65 mbsf marks a major hiatus of up to 5 m.y. in duration. Between 306.65 and 409.36 mbsf, correlation with the MPTS is not possible because only normal polarity is identified and there are no additional age constraints. Beneath 409.36 mbsf, $^{87}Sr/^{86}Sr$ ratios, diatom datums and diatom and marine palynomorph assemblages provide general constraints on the age of the strata. However, the rapid sediment accumulation rates and the presence of numerous polarity zones, some of which may represent cryptochrons or geomagnetic excursions and may not have correlatives in the MPTS, makes correlation with the MPTS difficult (Fig. 10).

While the presence of multiple stratigraphic hiatuses makes definitive correlation with the MPTS difficult for much of the CRP-2/2A succession, the resulting age model demonstrates that average sediment accumulation rates were rapid (100 – 1000 m/m.y.) and that much of the record is missing in multiple hiatuses.

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